Numerical Investigation of Radar Scattering from the Sea Surface at Small Grazing Angles

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LONG-TERM GOAL

The research project focuses on the understanding of electromagnetic scattering from the ocean surface at small grazing angles. The long-term goal is to investigate the validity of existing distributed-surface, edge-diffraction, multi-path, and shadowing scattering theories when applied to the sea surface at small grazing angles.

OBJECTIVES

The short-term objectives are to a) numerically characterize the electromagnetic scattering from modeled and measured water surface profiles, b) to compare the results with existing scattering models, and c) to improve the accuracy and efficiency of the techniques themselves.

APPROACH

The scattering from measured and modeled sample one-dimensionally rough water surfaces is being calculated using two distinct extensions of the standard moment method (MM) that allow application at arbitrarily small scattering angles. The first method is a hybrid approach that extends the moment method using the geometrical theory of diffraction (GTD). The front and back faces of the surface are extended to infinity, eliminating the need for an illumination weighting function that limits the efficiency of standard MM when applied to rough surfaces at small grazing angles. Single basis functions derived from GTD are used to describe the current on the infinitely extending surfaces, limiting the computational expense of the approach. The other extended MM approach treats the surface as periodic, again giving an infinitely extending surface that eliminates the need for an illumination weighting function. Finite conductivity water surfaces are treated using impedance boundary conditions. Iterative solution of the linear system resulting from the moment method is being used to allow larger surfaces to be treated.

WORK COMPLETED

The scattering from a series of surfaces representing the time-evolution of a spilling breaker has been found using the hybrid MM/GTD impedance-boundary approach. The surfaces were experimentally measured in a wave tank using a laser measurment system. The time dependence of the horizontally (HH) and vertically (VV) polarized backscattering has been examined, as has the Doppler shift induced

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in the backscatter by the breaker motion. The ability of the two-scale scattering model to predict the backscattering as the breaker evolves has been examined.

A study of iterative techniques to solve the system of linear equations resulting from the descretization of integral equations within the moment method has been completed. The relative performance of various stationary and non-stationary iterative approaches under realistic scattering condtions has been benchmarked. A formulation of the impedance boundary condition that dramatically reduces the number of iterations needed to solve for the HH scattering has been implemented.

RESULTS

The time sequence of the spilling breaker is shown in Figure 1. The wave is propagating from right to left. The measurement system was mounted on a carriage moving at the wave phase velocity so the crest remains centered in the figure at all times. Initially (zero time) the wave crest is rounded, but steepens with increasing time. At time 0.25 s parasitic capillary waves appear on the front face of the wave, and shortly thereafter a distinct plume appears at the crest. The crest is re-entrant for a short period before 0.4 s. At 0.4 s the crest collapses, giving freely propagating capillary waves whose phase velocities are smaller than that of the large-scale wave and therefore appear to move down the back face of the large wave.

The 10 GHz scattering from the wave profile of Figure 1, calculated assuming the scattering surface dielectric properties are those of sea water, is shown in Figure 2. The EM energy was incident from the left at 10^{o} grazing. Prior to 0.12 s the scattering from the wave is quite small and only spurious response from the pixelization error of the surface measurements appears. As the wave steepens and becomes re-entrant the scattering increases dramatically, with VV averaging about 10 dB above HH. No sea spike response (HH > VV) appears since the front face of the wave is truncated in the surface description and no multipath interference can occur. When the crest collapses just after 0.4 s the average VV scattering remains approximately constant (or decreases slowly), while the average HH scattering drops much more rapidly. The behavior after 0.4 s is consistent with the predictions of the two-scale scattering model, and in fact a direct application of the perturbation equations that are the basis of the two-scale model gives a good prediction of the scattering. At earlier times the backscattering is due to direct diffraction from the sharpening crest or quasi-specular reflection from the re-entrant breaker plume. The Kirchhoff approximation scattering model is unable to accurately predict the scattering in either of these cases. The phases of the scattering was maintained in the numerical calculations to allow the calculation of the time dependence of the Doppler shift of the backscattering. Prior to 0.4 s the observed shift corresponded to the phase velocity of the large-scale wave. This is consistent with the diffraction/quasi-specular reflection scattering mechanism already suggested. Later the Doppler shift decreases with increasing time, as expected with Bragg-resonant scattering from freely propagating capillary waves carried by the orbital motion of the large-scale wave.

It has been shown that the forward-backward and MOMI iterative procedures that have been used recently in scattering calculations are mathematically equivalent to the symmetric successive over-relaxation (SSOR) stationary iterative procedure for solving algebraic systems of linear equations. The extended Kirchhoff approximation is similarly equivalent to Jacobi iteration. Convergence problems that are sometimes observed with these approaches are due to inherent limitations of stationary techniques. A comparison with non-stationary procedures that are designed for improved robustness has been performed. The results for the scattering from a finite conductivity breaking water wave (the spill wave

of West *et al.* (1998), calculated using the impedance boundary MM/GTD approach described in that paper at 9 GHz and 10^{o} grazing) are shown in Figures 3 and 4 for VV and HH polarizations respectively. The non-stationary iterative schemes considered are bi-conjugate-gradient-stable (BICGSTAB), quasi-minimum residual (QMR), general minimum residual (GMRES), conjugate-gradient normal equations (CGNR), and generalized conjugate residual (GCR). At VV the quickest convergence is achieved with SSOR/MOMI iteration, with somewhat worse performance with BICGSTAB. At HH BICGSTAB initially shows the most rapid convergence, achieving a normalized residual of 10^{-4} (adequate for most scattering calculations) first, but later SSOR/MOMI is more rapid. Jacobi iteration diverges immediately in this case. With the badly conditioned systems that result when scattering resonances occur SSOR/MOMI can also diverge. The non-stationary approaches have proven much more robust in these cases, eventually converging, albeit slowly.

At vertical polarization it has proven most convenient to use the moment method to treat a magnetic field integral equation (MFIE) that matches the tangential magnetic field at the boundary for one-dimensionally rough, perfectly conducting surfaces. This is a second-type integral equation that yields a well-conditioned linear system that is well suited to iterative solution. This has also proven true when a finite conductivity surface is considered, as demonstrated by the performance in Figure 3. The most straightforward approach to treat horizontal polarization is to apply duality to the VV equations, yielding an integral equation that matches the tangential electric fields (West *et al.*, 1998; Holliday *et al.*, 1998). Unfortunately, for high conductivity scattering media such as sea water this yields a badly conditioned linear system that can diverge or converge slowly as in Figure 4. On the other hand, matching the magnetic field at horizontal polarization gives better conditioning at the expense of a strong singularity in the integral equation kernel that can lead to numerical inaccuracies unless specially treated. It has been determined that the inaccuracies can be avoided by numerically integrating the MM interaction terms near the diagonal which represent a close spacing between the source and observation points. This is shown in Figure 5, which compares the calculated HH scattering from the breaking wave when the electric field is matched, and when the magnetic field is matched with integration of interaction terms. Agreement to within 0.2 dB is achieved at all incidence angles. The performance of the iteration schemes when matching the magnetic field is shown in Figure 6. In this case the quickest convergence to any normalized residual is achieved with BICGSTAB, and a factor of three improvement over matching the electric field is realized. In the cases examined, BICGSTAB appears to give a good compromise between convergence speed in the well conditioned cases and robustness with ill conditioning.

IMPACT/APPLICATION

The numerical treatment of the measured breaker demonstrates that scattering from a small breaking wave can result from a non-Bragg-resonant mechanism. The Doppler shift associated with the non-Bragg scattering corresponds to the phase velocity of the breaking wave while the later Bragg scattering gives a lower Doppler shift. This demonstrates a mechanism by which the “slow” and “fast” scattering observed experimentally in sea-scatter measurements may be generated. It also shows that both slow and fast scatterers may be generated by the same breaking event.

Identification of the mathematical equivalence of recently introduced iterative scattering techniques to known stationary techniques for solving linear systems demonstrates that several other options are also available for the calculations. Often it may be more cost effective to apply a more robust non-stationary iterative technique to an existing, poorly conditioned integral equation formulation to achieve obtain

slow convergence rather than use the human resources to reformulate the problem with better conditioning that is optimized for the stationary techniques.

TRANSITIONS

The Jacobi iteration routine developed for the comparison described above is being used to examine the accuracy of analytical scattering models based upon iterative application of the Kirchoff approximation. The results are being used by Scott Chubb (NRL) and Donald Thompson (Johns Hopkins/APL).

RELATED PROJECTS

The spilling breaker profiles of Figure 1 were provided by James Duncan (University of Maryland). The numerical calculations are being performed on DEC Alpha work stations procured under ONR DURIP grant N000149810277.

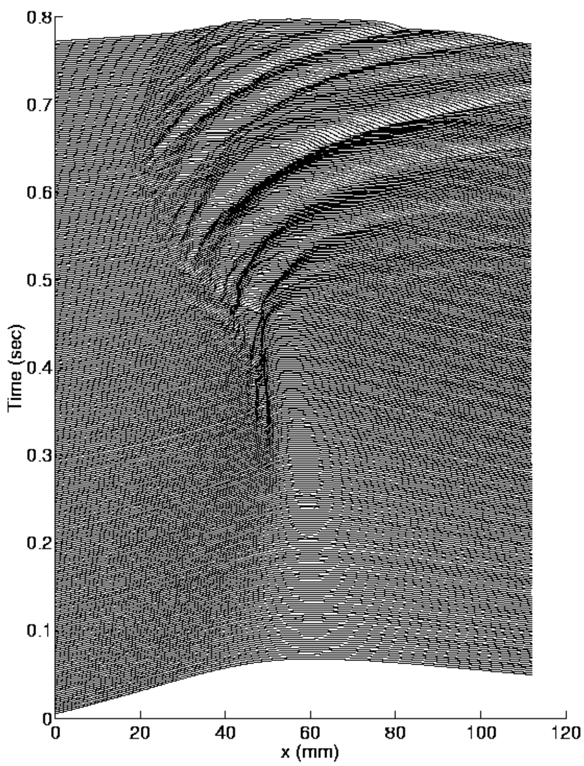

Figure 1

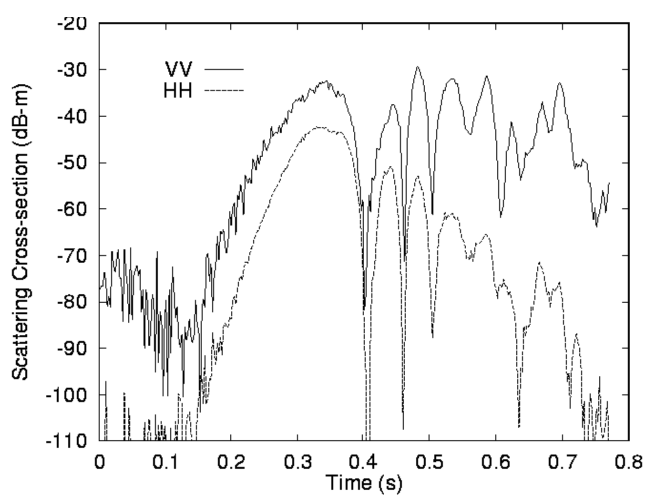

Figure 2

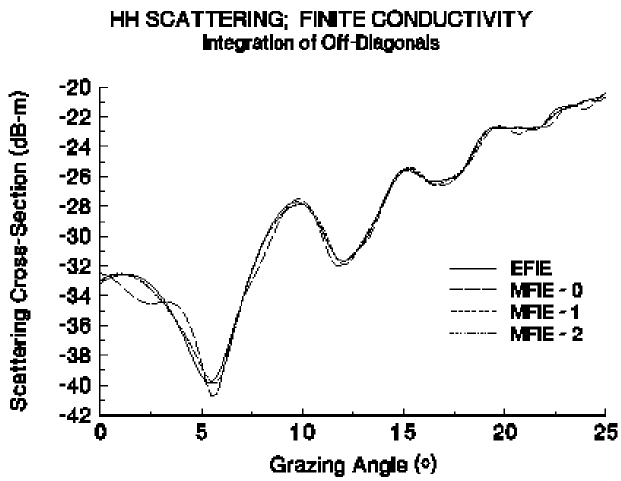

Figure 3

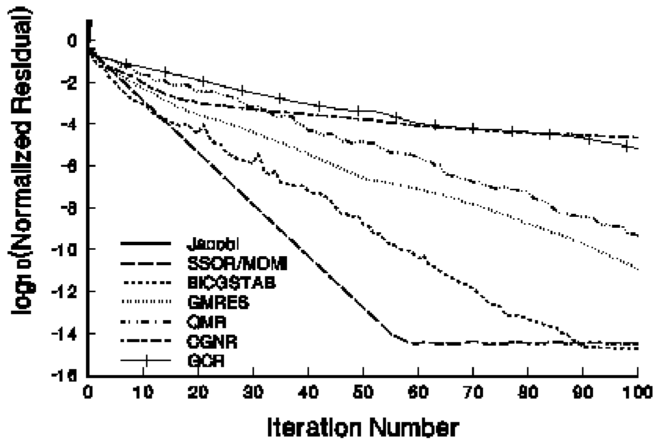

Figure 4

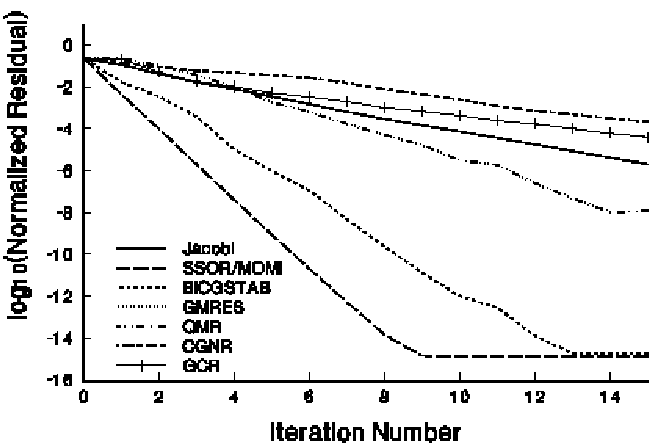

Figure 5

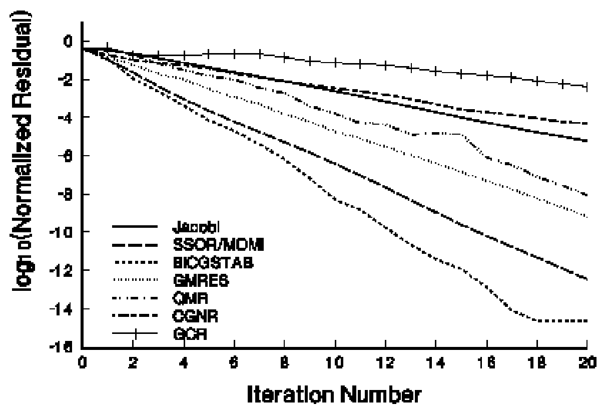

Figure 6

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